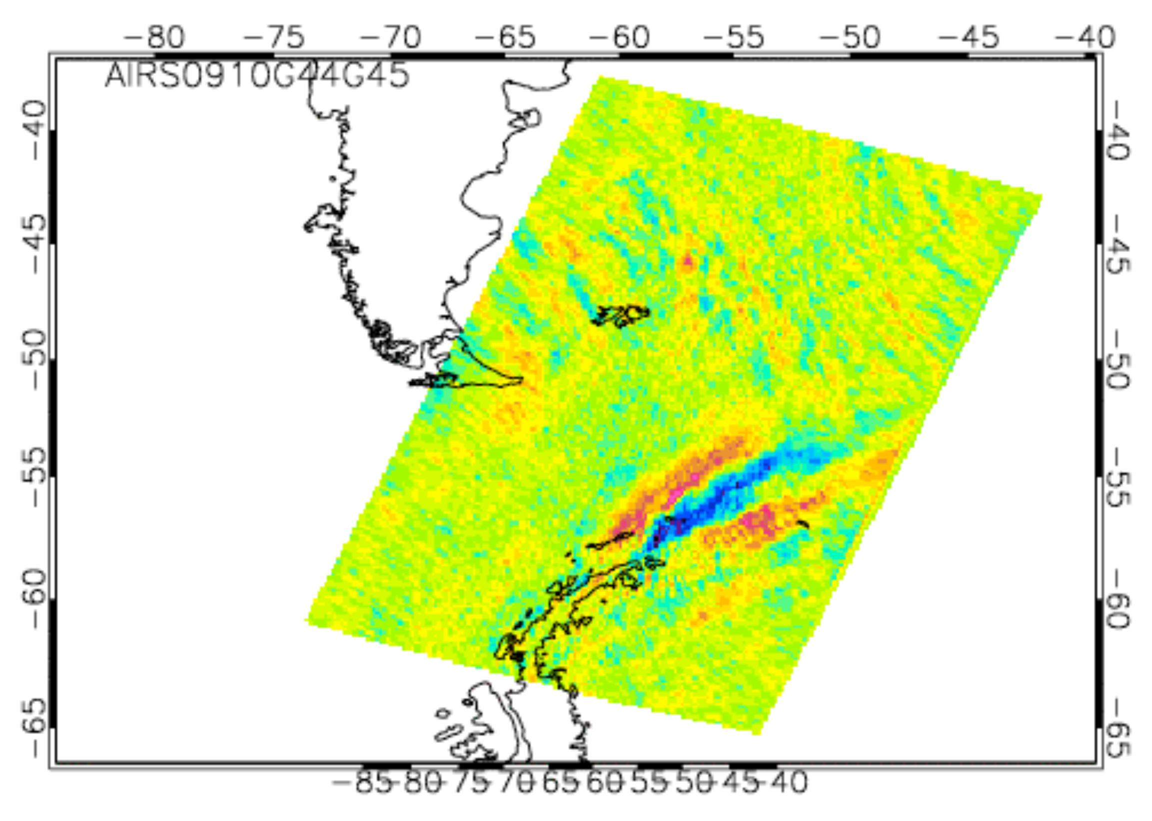
Analysis of a Mountain Wave Event Observed in AIRS and ECMWF

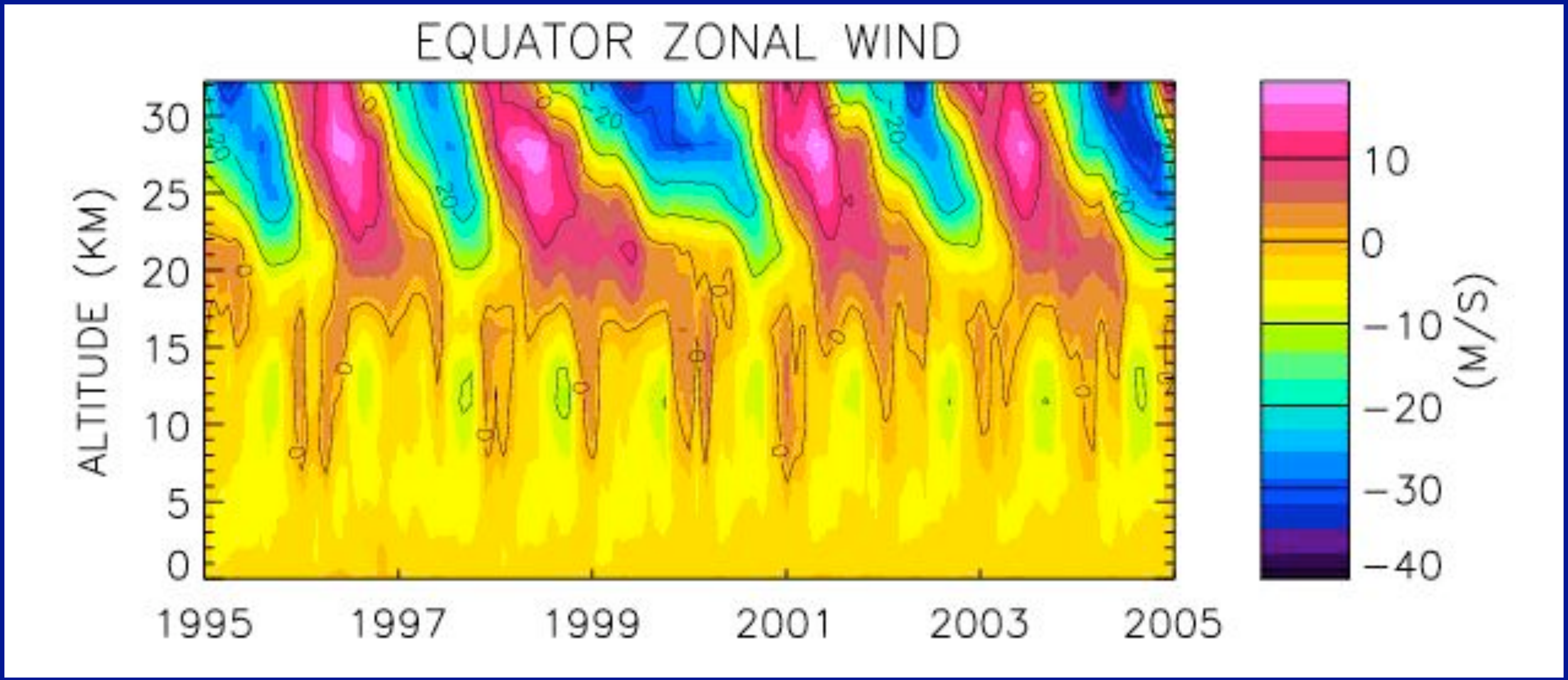
Joan Alexander, *NorthWest Research Associates*



667.7 cm^{-1} channel radiance perturbations showing a gravity wave event in the stratosphere

Atmospheric Gravity Waves:
Global Effects on the Circulation

- Gravity waves are internal waves with small-scales compared to global.
- They naturally grow in amplitude with height because of conservation of energy and the exponential decrease in atmospheric density with height.
- They carry vertical flux of horizontal momentum through the atmosphere.
- Upon breaking (dissipating), they drive large-scale circulations.

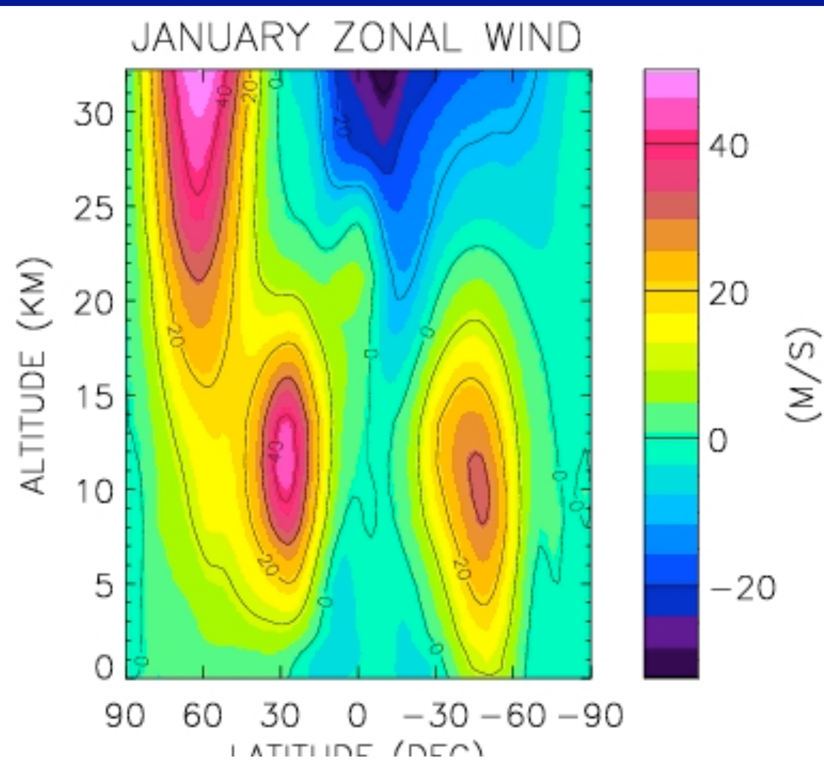


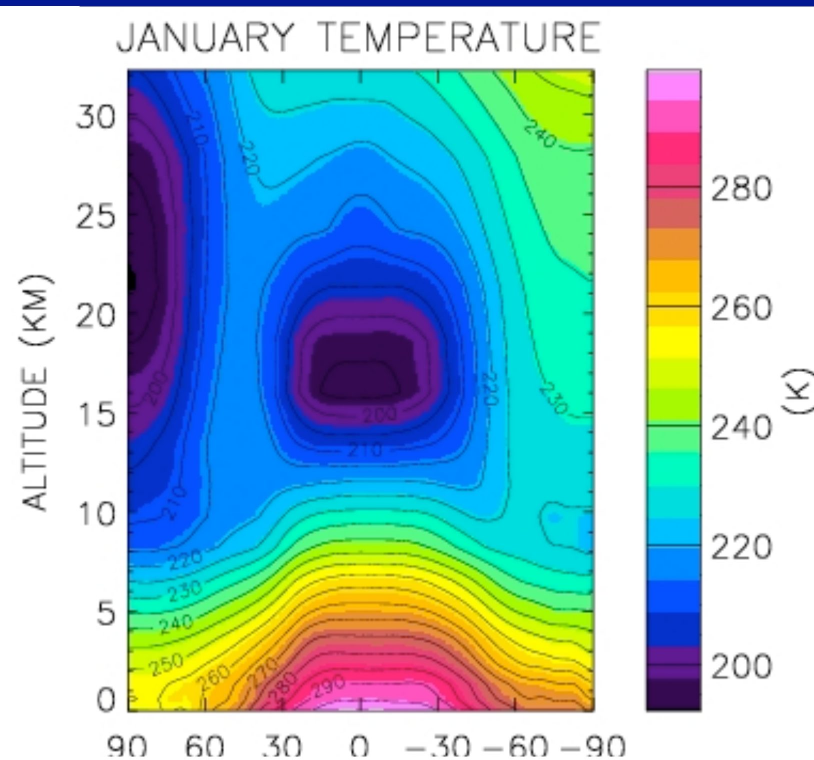
The Quasibiennial Oscillation (QBO) is a classic example of a wave-driven circulation. Roughly half of the wave momentum flux is carried by small-scale gravity waves.

Atmospheric Gravity Waves:

Global Effects on the Circulation

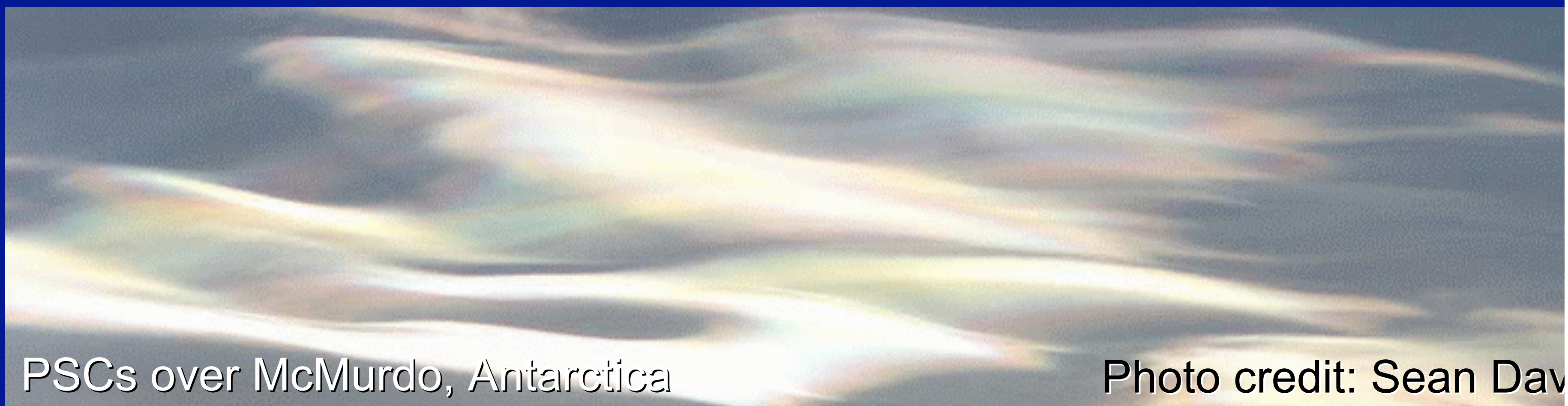
- Mountain wave drag slows the winter jet in the upper troposphere and stratosphere and helps to correct a “cold pole problem”.
- Currently treated via parameterization in climate and forecast models.
- The wave momentum flux is dependent on sub-grid-scale topographic variance, surface winds, stability, and tunable parameters.





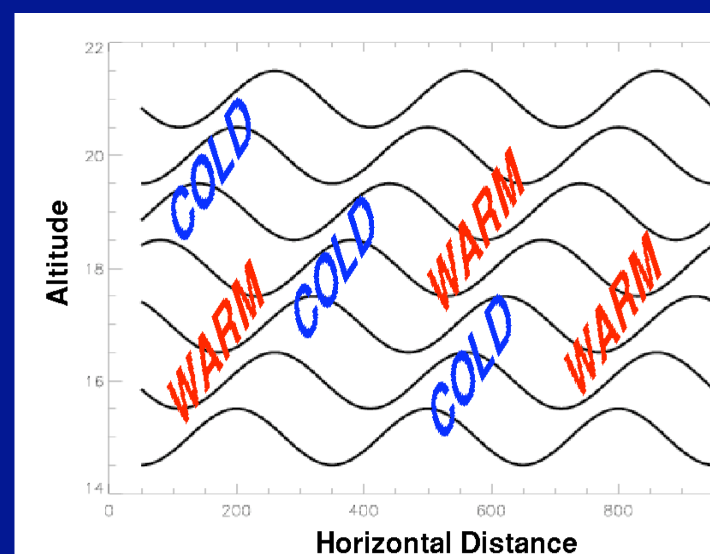
Atmospheric Gravity Waves:

Global Effects on Clouds and Chemistry



- The "cold pole problem" leads to large errors in temperature-sensitive ozone chemistry in the stratosphere.

- Gravity wave fluctuations can cause polar stratospheric clouds to form in conditions that are otherwise too warm.



Parameterization of Mountain Wave Drag

(a forcing term for the RHS of the momentum equation)

Inputs:

- Wave momentum flux (function of surface wind subgrid orography)
- Horizontal wavelength
- Wave phase speed =0
- Direction of propagation (opposite surface wind)
- Background wind and stability profiles

- These determine the altitude where the waves break or dissipate.
- 1-D Wave propagation is assumed (vertical column calculation).
- The mean-flow force is proportiona to the vertical gradient of momentur flux and the force direction will always “drag” the mean-flow towarc the wave phase speed.
- Mountain waves are stationary; the therefore always act to slow the me flow speeds towards zero.

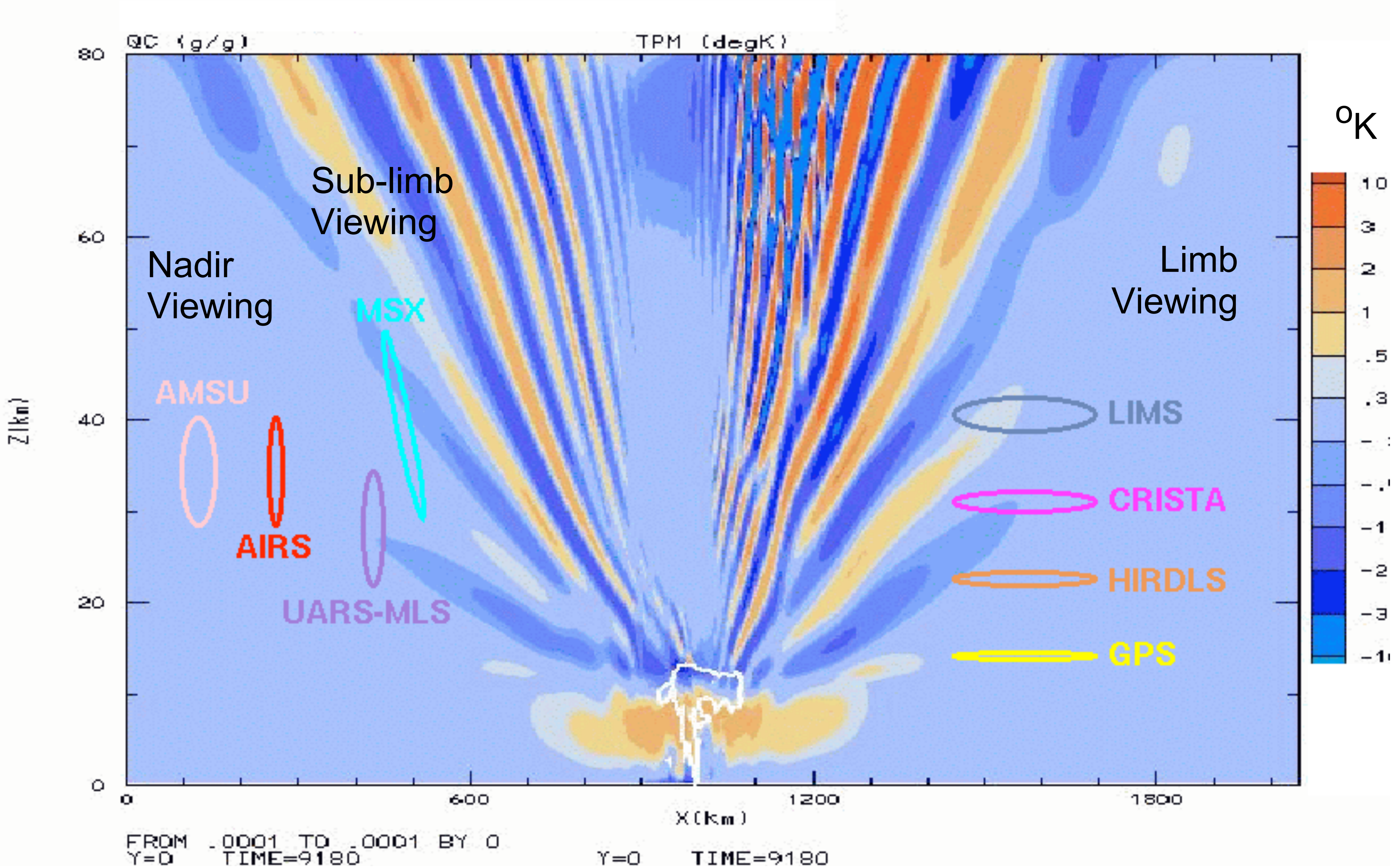
Momentum Flux from Satellite Observations of Gravity Wave

- AIRS observes *T'* (temperature amplitude)
- To convert to momentum flux, also need:
  k = horizontal wavenumber
  m = vertical wavenumber
  ϕ = propagation direction

Momentum Flux ~ $(k/m)\,|T'/T|^2$

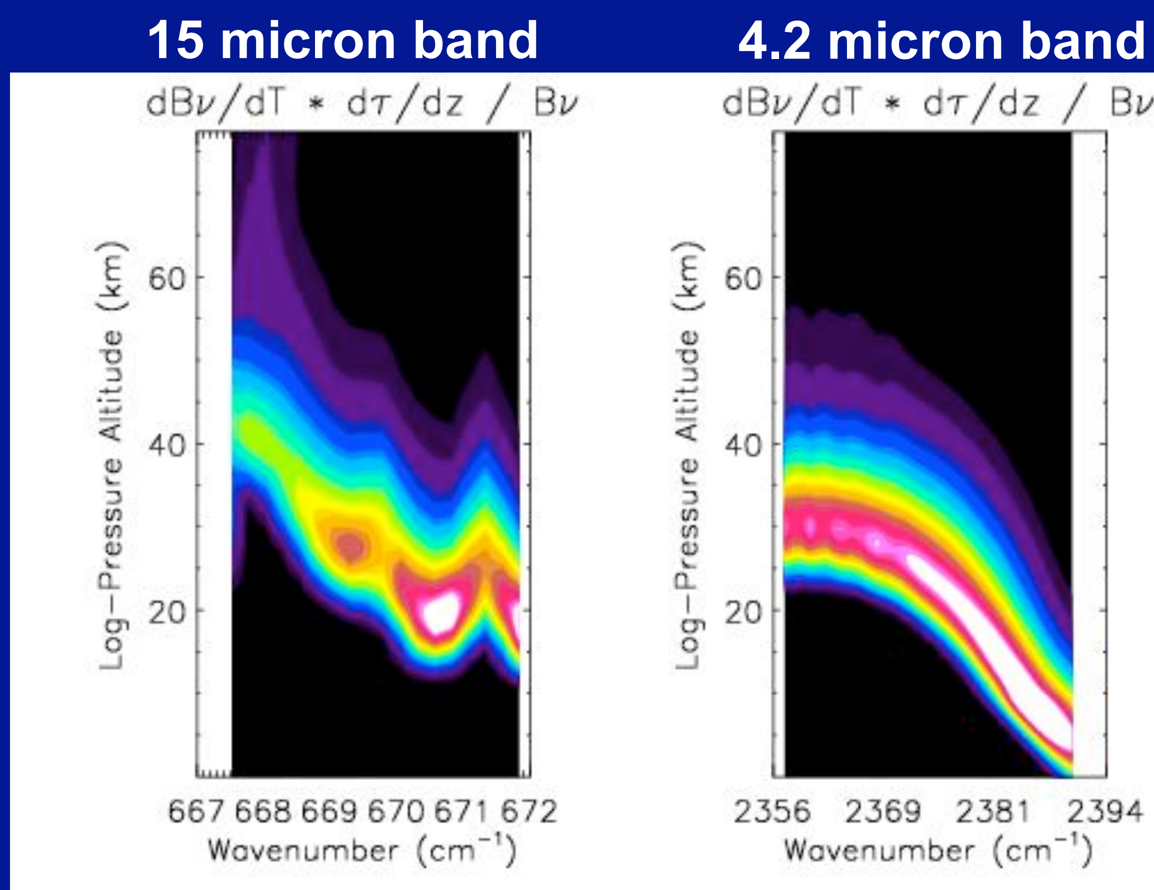
- For a given *T'*, momentum flux will be larger for longer vertical and shorter horizontal wavelength waves
- $T'(k,\phi)$ observed directly from AIRS high resolution images
- For mountain waves, $m = N/U$ (buoyancy frequency/wind speed)
- For nonstationary waves, *m* must be computed from observations.

Effective Weighting Functions
for gravity wave observations
(schematic)



AIRS CO_2 Temperature Sensing Channels

Kernel Functions

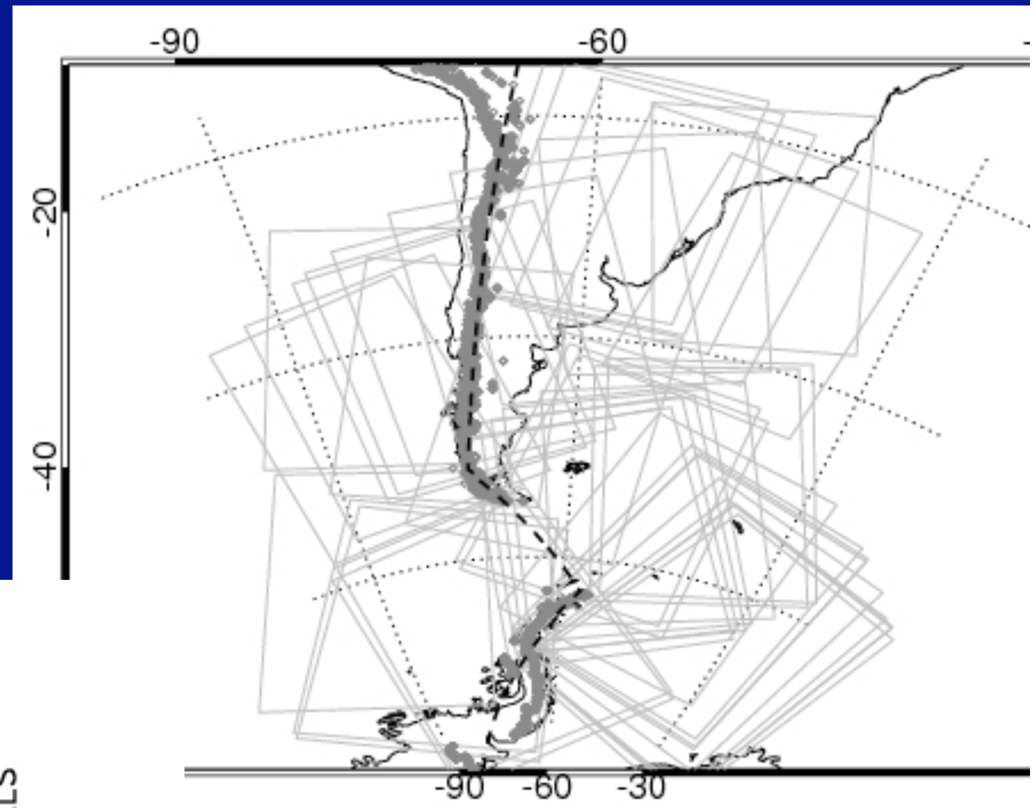


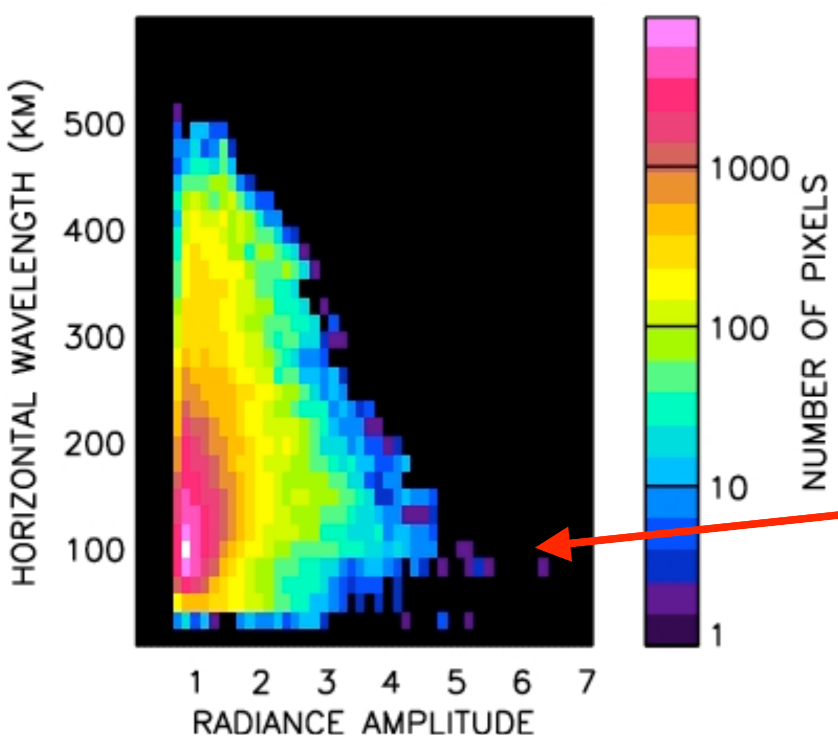
- Gravity waves are detected in the AIRS temperature-sensing channels
- Clouds interfere when weighting functions intersect cloud tops.

Mountain Wave Study: Distributions of Wave Properties from AIRS

Alexander and Barnet [2007]

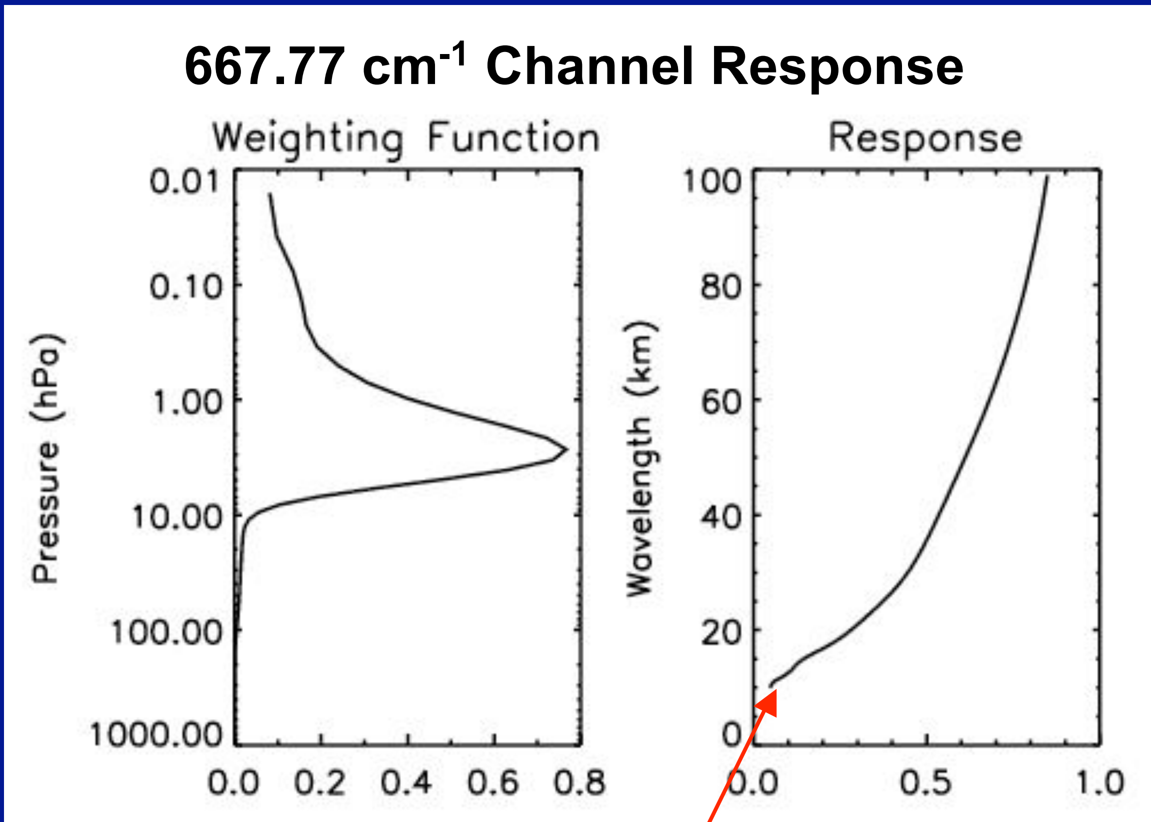
Distribution of wave amplitudes and horizontal wavelengths derived from 40 radiance granules at 667.7 cm^{-1} in the stratosphere over Patagonia and the Antarctic Peninsula



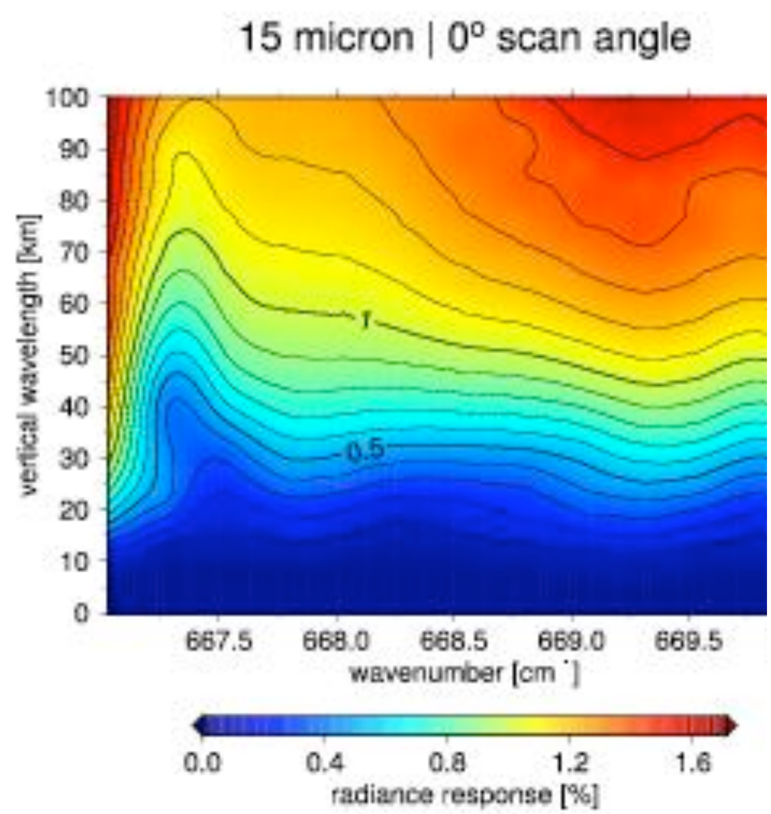


- Peak amplitudes for horizontal wavelengths of ~ 100 km.
- Loss of resolution in temperatur retrievals (Δx ~ 20 km -> 60 km) is a severe drawback.

Vertical Wavelength Sensitivity



Response vs Vertical Wavele
in the 15 μm band

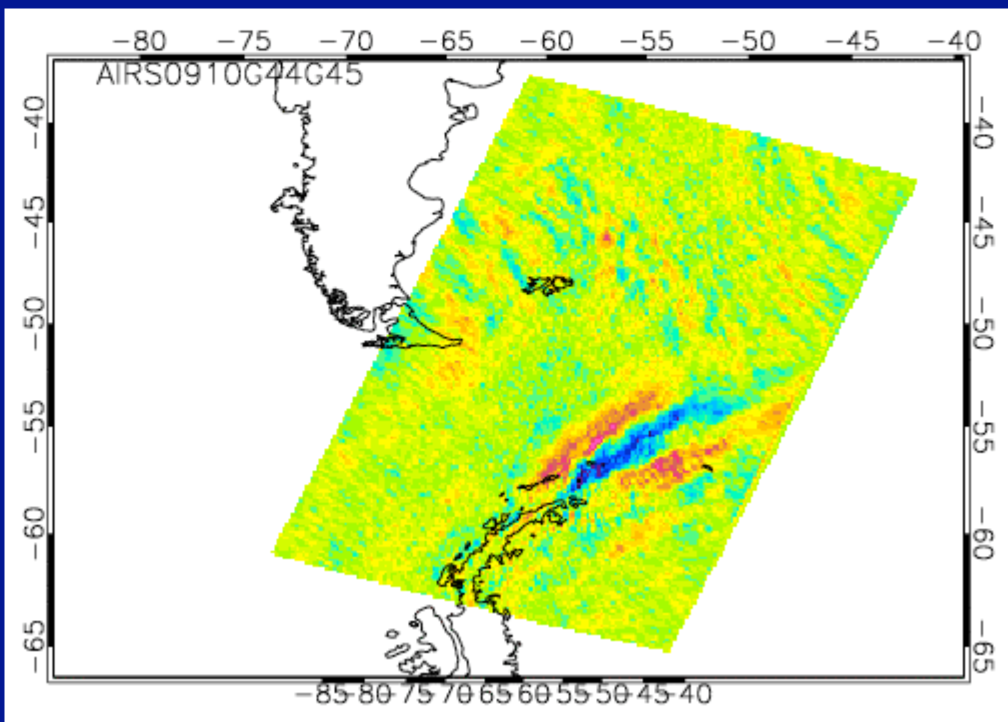


The depth of the weighting functions and the near-nadir view angles of AIRS mean there is little or no response to waves with vertical wavelengths less than 12 km.

Case Study 10 September 2003 [Alexander & Teitelbaum, 2006

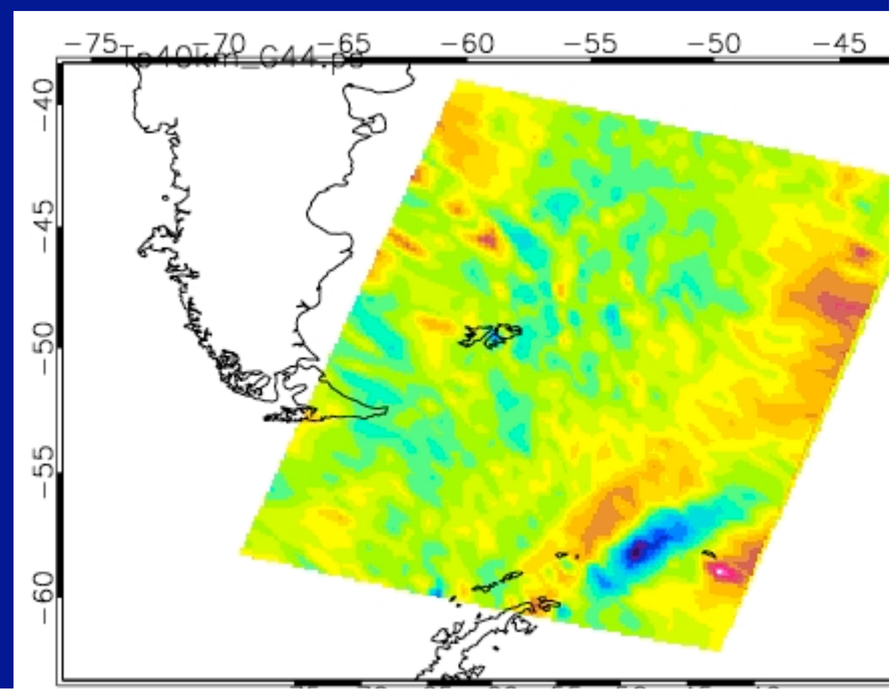
- Large amplitude wave event near the Antarctic peninsula
- Also seen in ECMWF forecast and assimilation fields

AIRS radiance at 667.7 cm^{-1}



- The horizontal wavelength is 300
in the stratosphere, large enough t
be resolved in the AIRS temperatu
retrievals.

AIRS temperature retrieval at 40 k

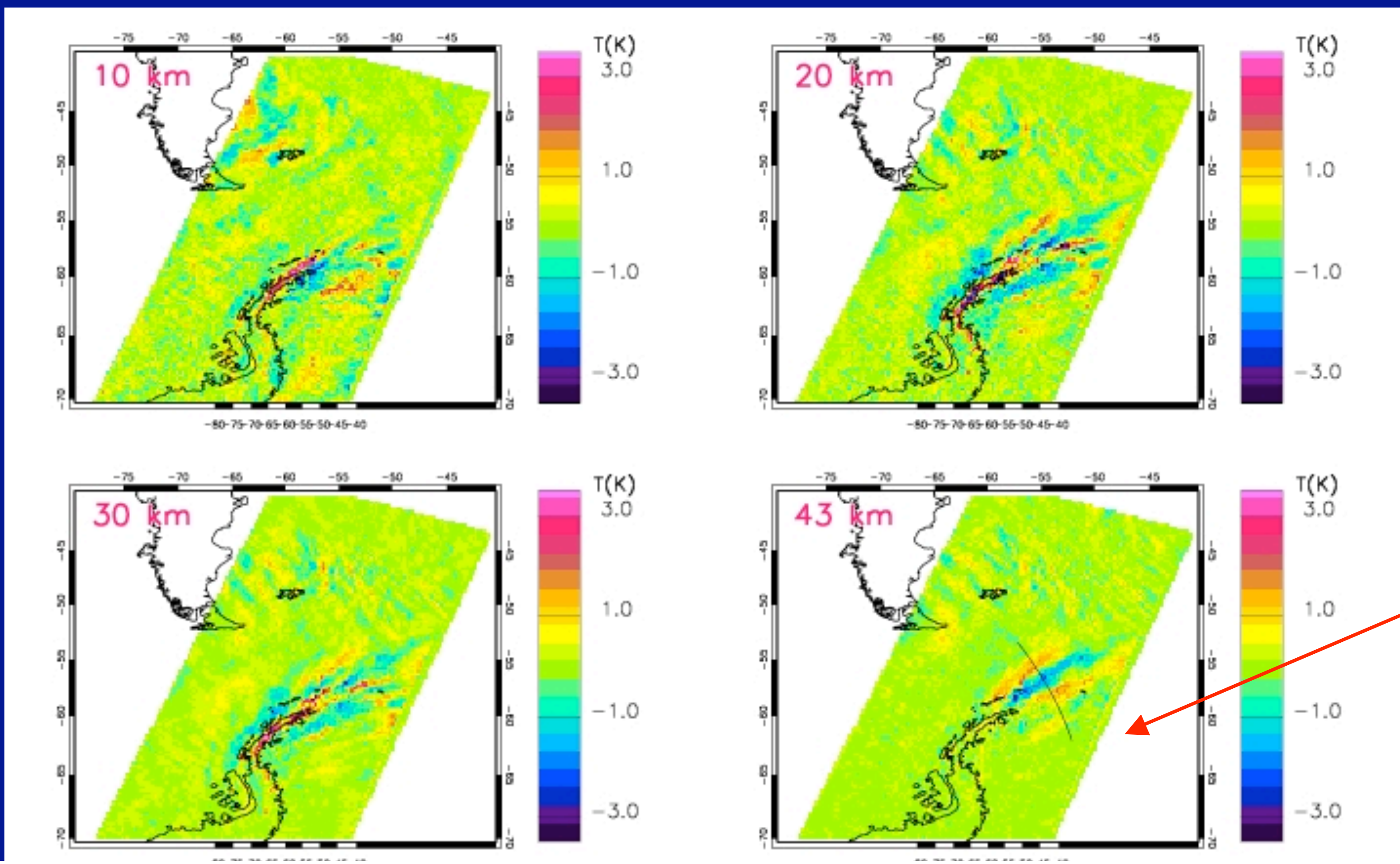


- Radiances have $\Delta x \sim 20$ km
- Retrievals have $\Delta x \sim 60$ km

Case Study 10 September 2003

- Compare radiances and temperature retrievals to ECMWF
- Focus on radiances because of higher horizontal resolution
- For small perturbations, the Planck function gives:

$$R'/R = T'/T\ (hc\nu/kT)$$



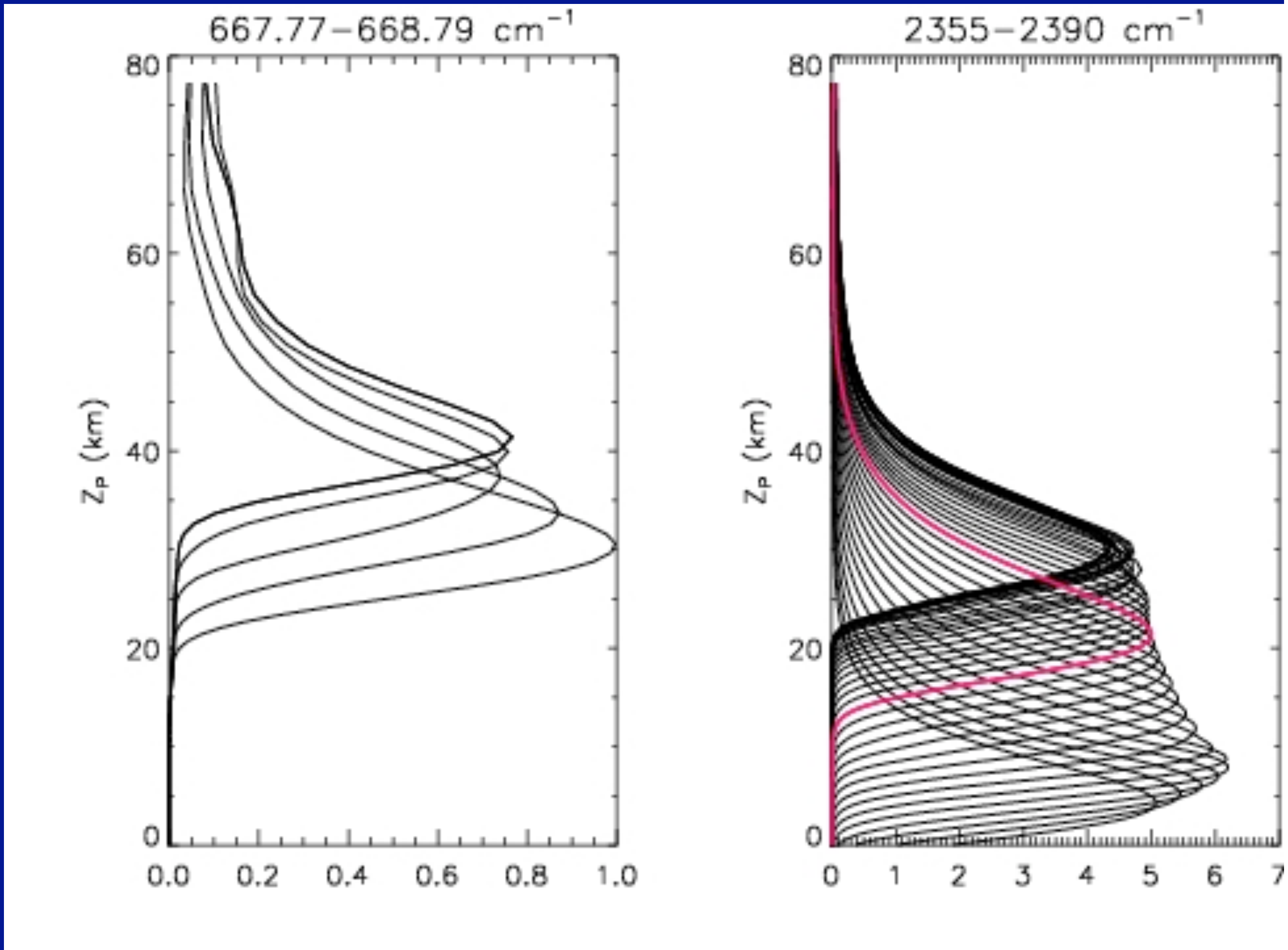
Location of cross-sections viewed in the following slide

Vertical gridding of radiances to create 3-d gravity wave images

- Selecting 34 channels in the stratosphere and troposphere
- Minimum height depends on cloud occurrence
- Vertical binned average weighted by (channel noise)$^{-1}$ = (neΔT)$^{-1}$

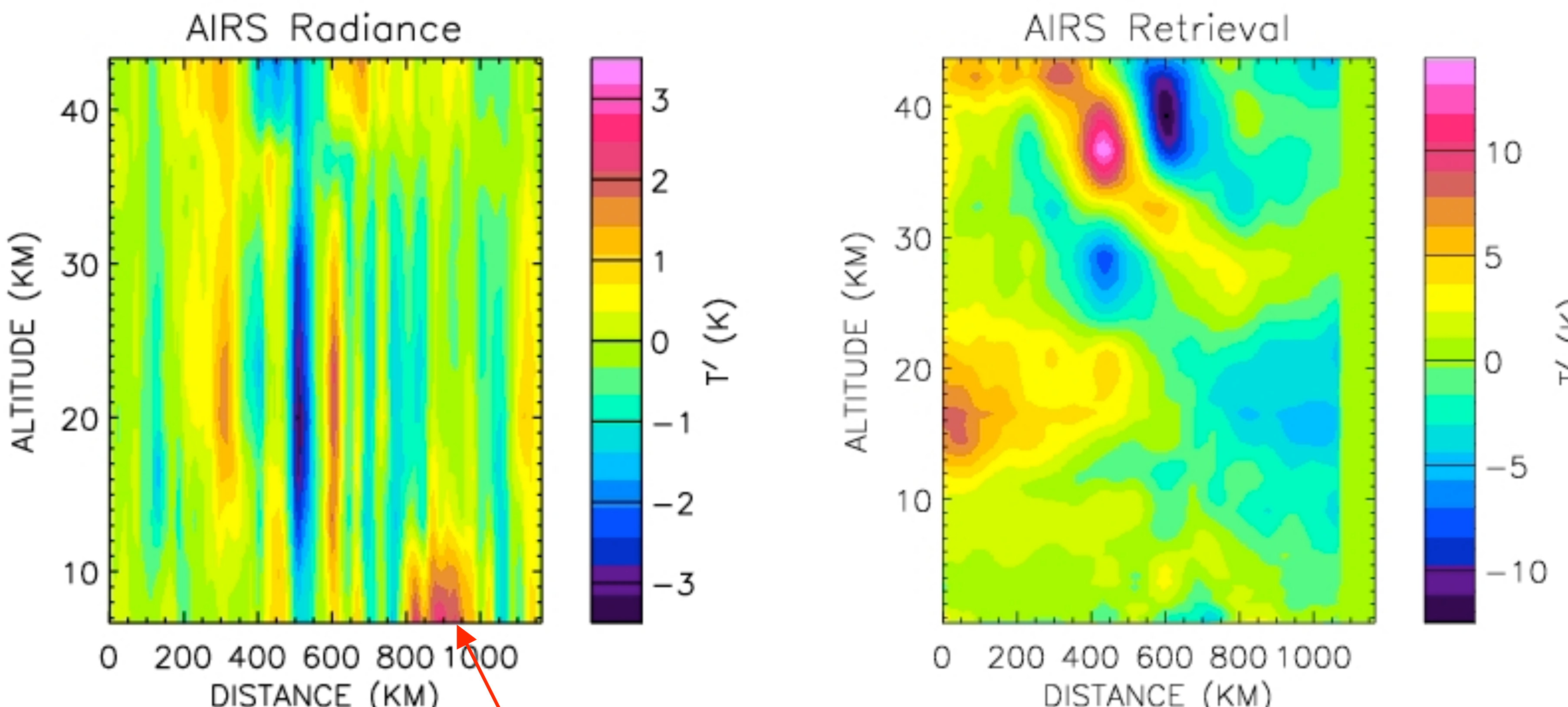
Gridded product noise varies from

K	z
0.15-0.29	>30km
0.04	~30km
0.09	<30km



Wave Event Vertical Cross-Sections

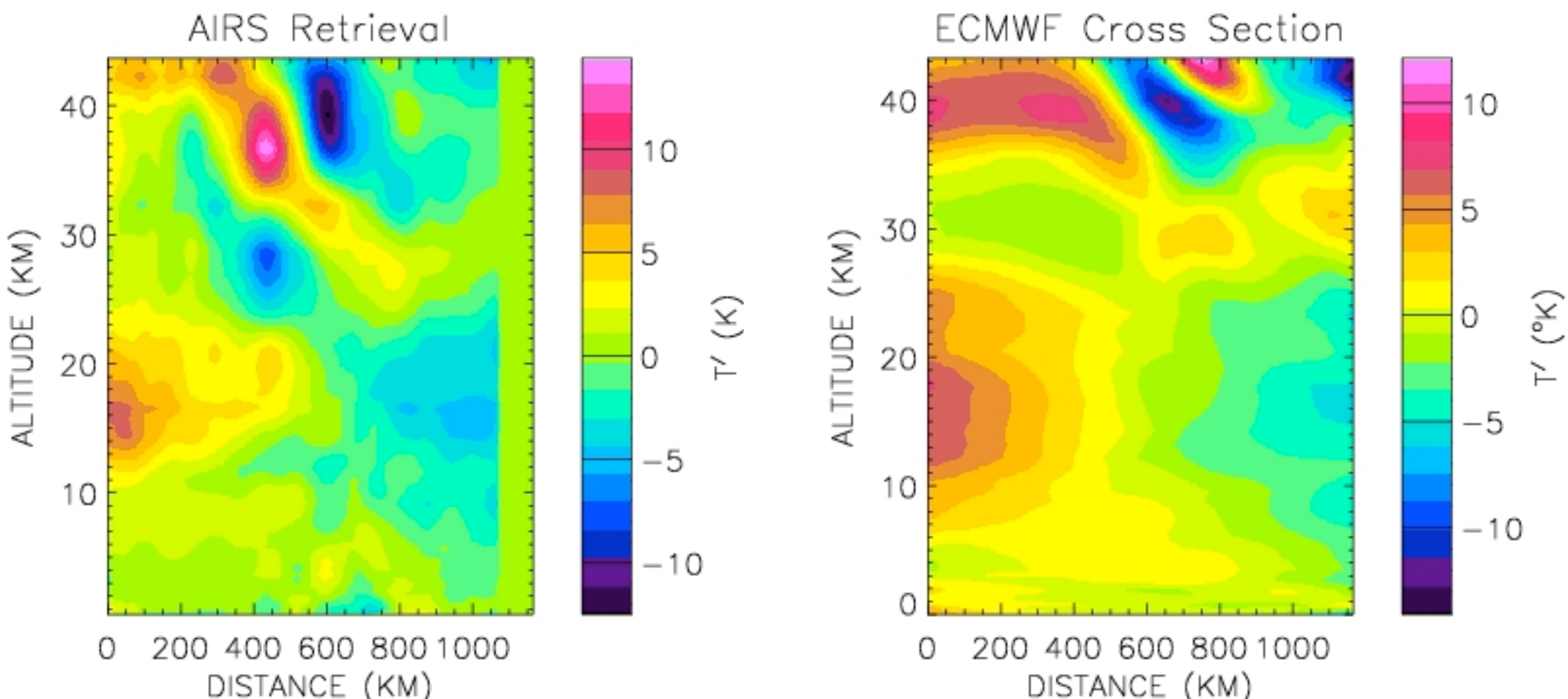
- The temperature retrieval sharpens vertical gradients. This correctly increases the wave amplitude above ~30 km.
- The radiance response function predicts a wave response of ~1/3 for a 20-km vertical wavelength wave.
- Below 25-30 km, the waves have smaller horizontal scales that are unresolved in the retrieval.



Cloud feature determined from auxiliary data

Wave Event Vertical Cross-Sections

- Comparison of AIRS retrieval and ECMWF shows remarkable similarity.
- We use the time resolution of the ECMWF to study the origin of this wave event.



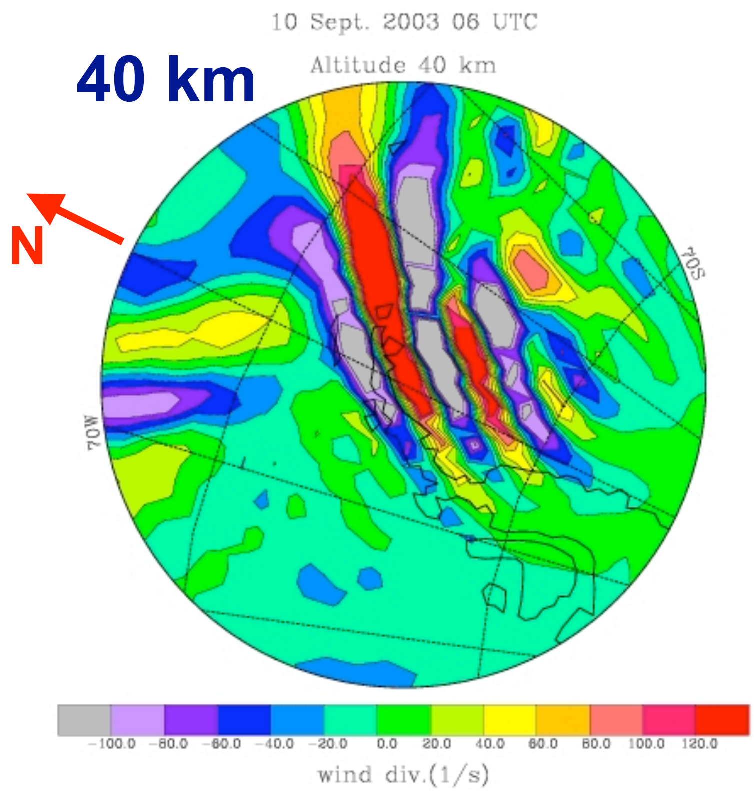
0420 UT

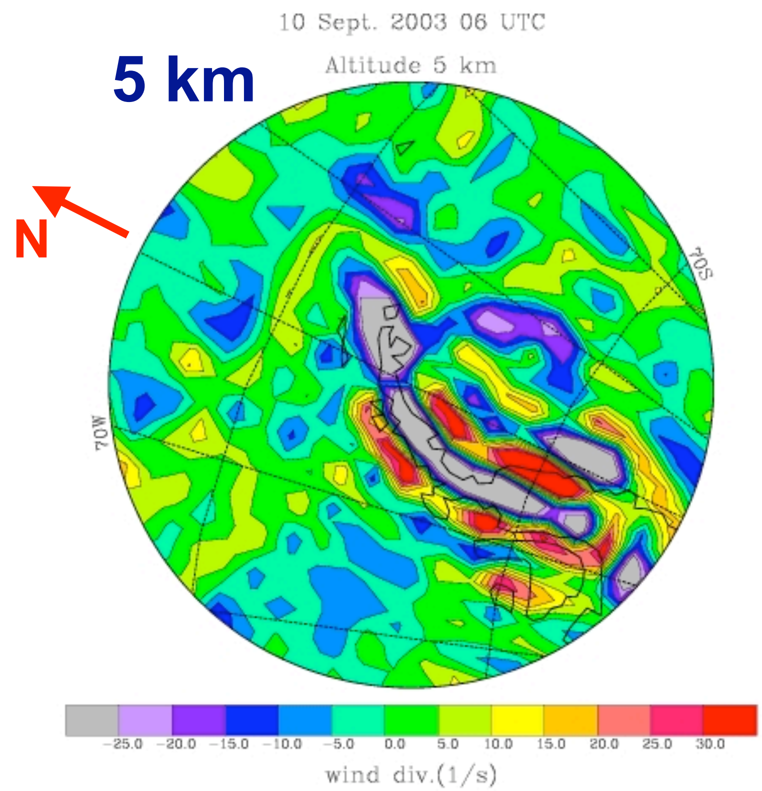
0600 UT

ECMWF Wind Divergence

isolates the wave from the geostrophic mean flow

- The ECMWF wave event has very similar scale and morphology.
- The perturbations appear directly above the peninsula at low altitude.
- At higher altitudes they appear north of the peninsula.



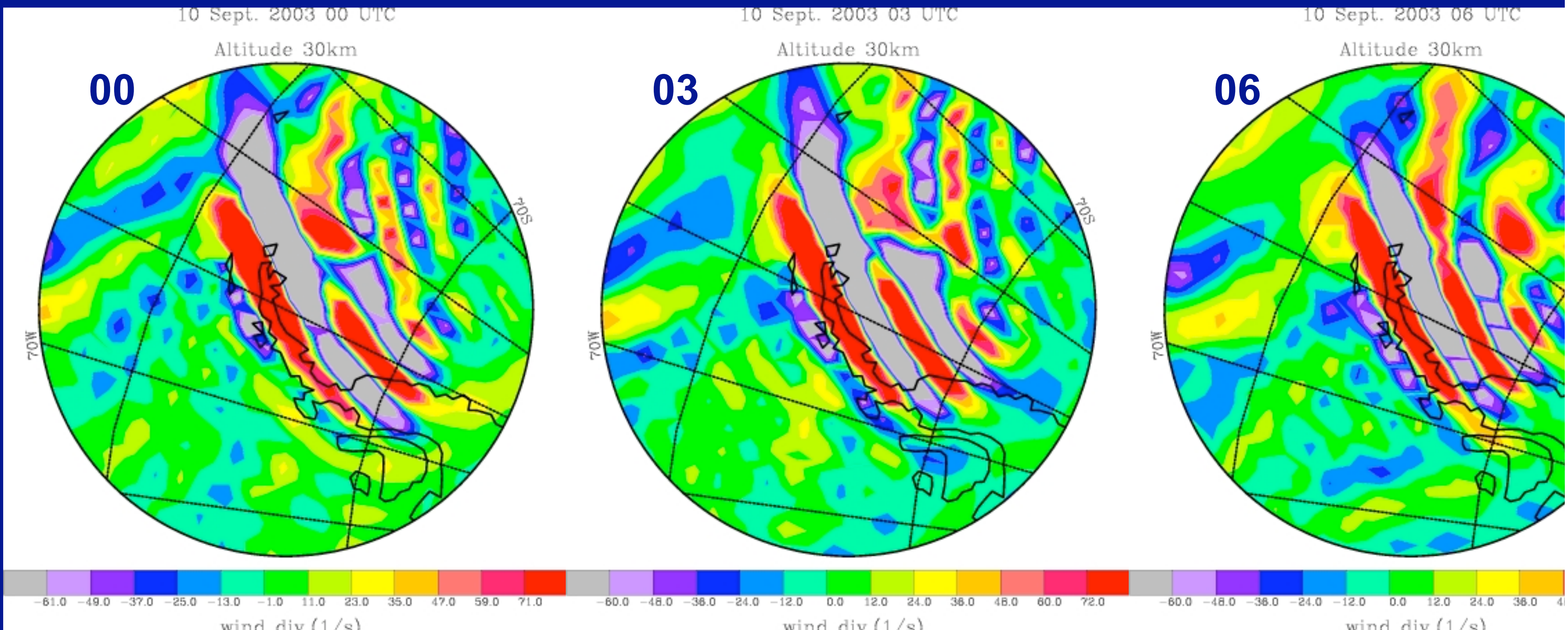


ECMWF Wind Divergence

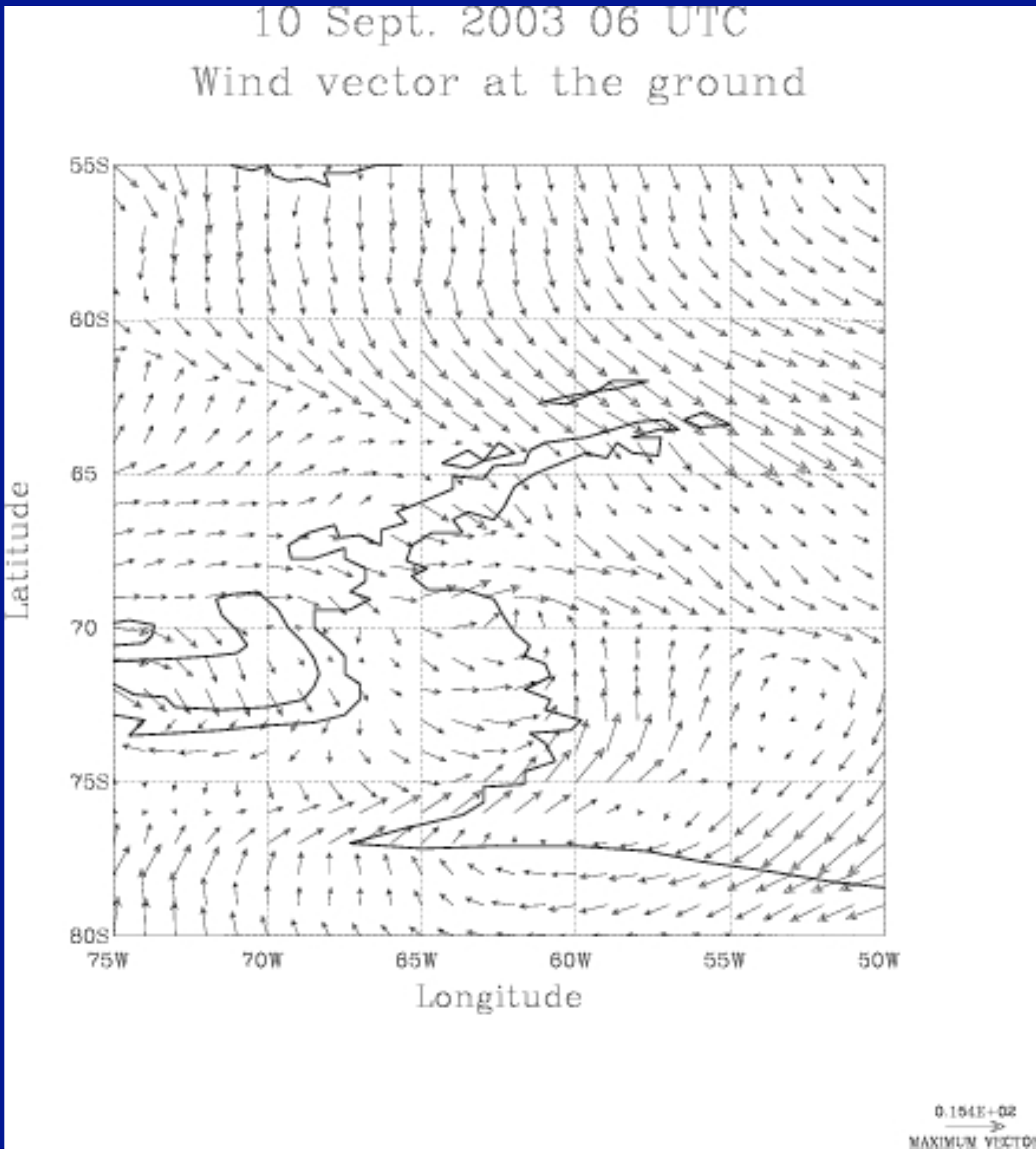
at z=30 km

three different times 00, 03, 06 UT

- The wave appears stationary relative to the peninsula topography
- The event persists for at least 18 hours from ~12 UT on 9 Sept to ~18 UT on 10 Sept
- Stationarity of the wave event is consistent with a mountain wave interpretation.



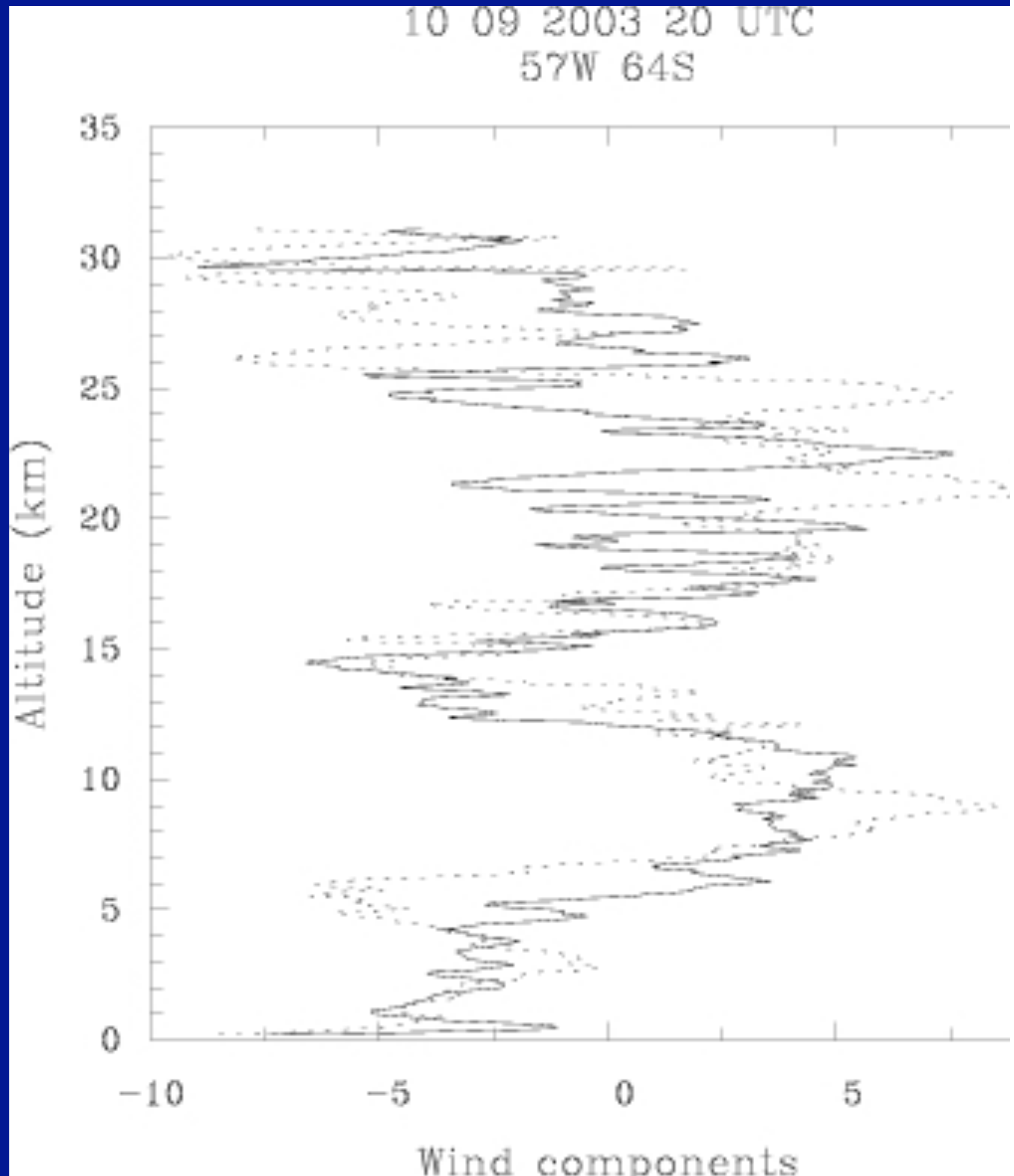
ECMWF Surface Wind Vectors



- Low level winds blow ~ perpendicular to the Antarctic peninsula ridge.
- Optimal orientation for large amplitude mountain wave forcin

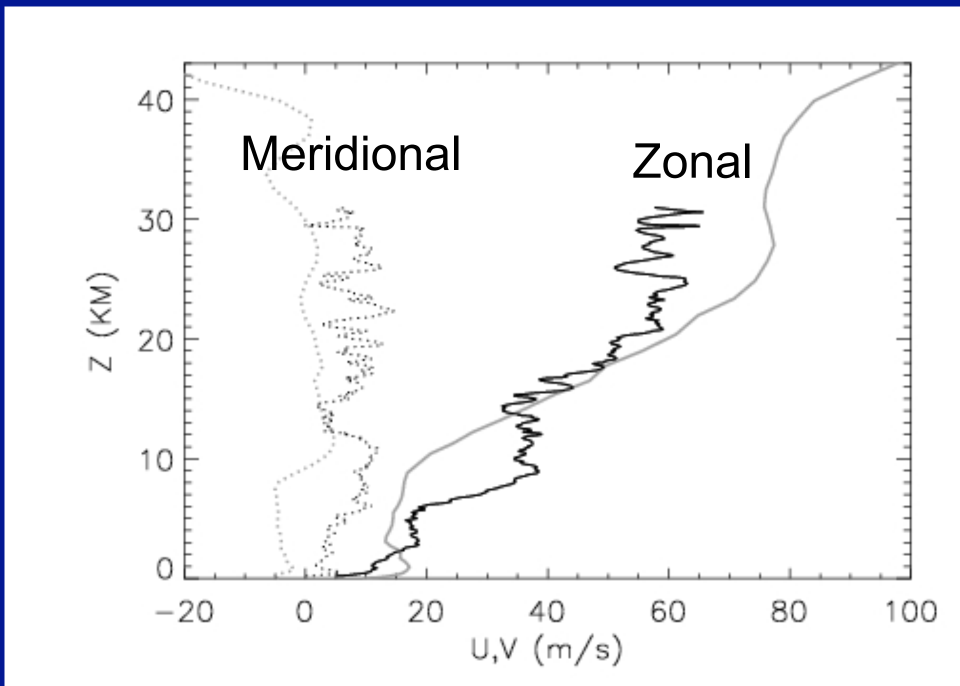
Marambio (57ºW, 64ºS) Radiosonde Analysis

- Detrended vertical profiles
- Two perpendicular components (u_R, v_R) in coordinate system rotated by 80º from cardinal directions
- Angle chosen to maximize the correlation coefficient between u_R and v_R
- Then u_R, v_R are in phase, and the coordinate system is aligned with the propagation direction of a medium frequency gravity wave
- This gives propagation direction ~opposite to the surface winds.



Background Wind Profiles and Theoretical Mountain Wave Vertical Wavelength

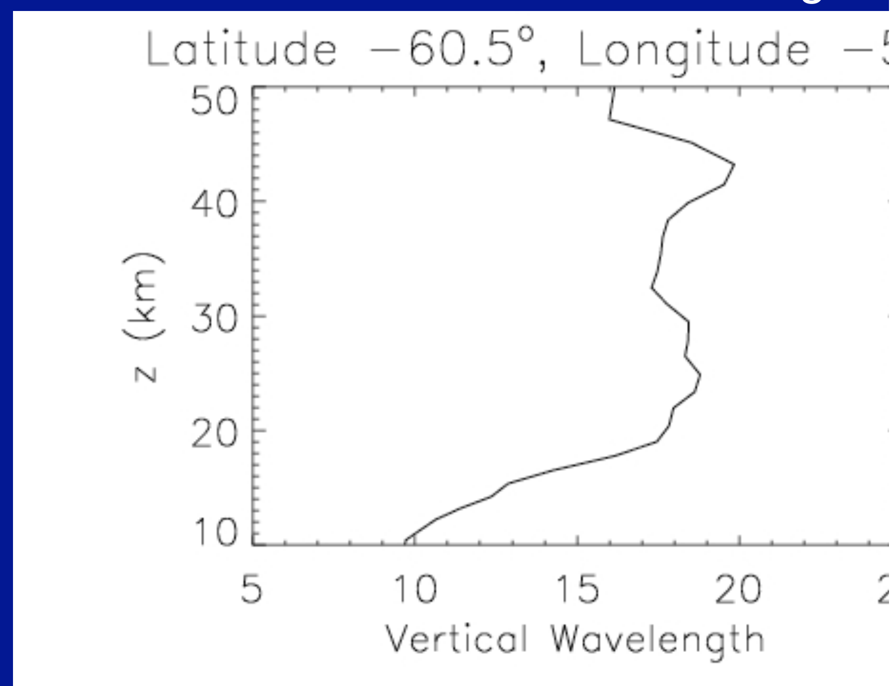
ECMWF and Radiosonde Wind Profiles



Using the gravity wave dispersio
relationship and winds in the mountain wave propagation direction:

$$\lambda_Z = N/(2\pi\, U)$$

Theoretical Vertical Wavelength



The observed vertical wavelength was 20 km at altitudes 40-43 km

Summary

- Analysis: AIRS radiance observations of a mountain wave event
  Horizontal wavelength = 300 km
  Vertical wavelength = 20 km
  Propagation direction 40^{o} west of north
- Vertical wavelength gives a radiance attenuation factor ~ 1/3 and estimated temperature amplitude ~ 10^{o}K (12^{o}K seen in the temperature retrieval)
- These allow estimation of the momentum flux using linear theory:

$$\text{Momentum Flux} \sim 1/2\rho(T'/T)^2(k/m)(g/N)^2$$

- **AIRS provides the necessary information to constrain input tuning parameters for gravity wave parameterizations.**
- Note: 1-D propagation becomes a poor assumption as models achieve higher horizontal resolution.